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A QUANTITATIVE FRAMEWORK TO ASSESS RESILIENCE AND RISK AT THE COUNTRY LEVEL

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Abstract

This paper presents a quantitative method to assess the resilience and the resilience-based risk at the country level. The approach is inspired by the classical risk analysis, in which risk is a function of vulnerability, hazard, and exposure. In the proposed analysis, resilience-based risk is a function of resilience, hazard, and exposure. In the new formula, the resilience parameter is evaluated using the data provided by the Hyogo Framework for Action (HFA). HFA scores and ranks countries based on a number of equally weighted indicators. To use those indicators in the resilience assessment, the contribution of each indicator towards resilience must be determined. To do that, three methods to weight and combine the different HFA indicators are proposed. The first two methods are based on the Dependence Tree Analysis (DTA), while the third method is based on a geometrical combination of the indicators using spider plots. The proposed methodology has been applied to a case study composed of 37 countries for which both the Resilience (R) and the Resilience-Based Risk (RBR) indexes have been determined.

Keywords: Community resilience; Vulnerability; Risk management; Hyogo Framework for Action; Resilience metrics

INTRODUCTION

Over the years, community resilience has attracted remarkable attention due to the increasing number of natural and man-made disasters. Communities that are able to absorb the impacts and recover quickly after disasters are fairly resilient

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communities, while communities whose recovery capacity is exceeded need to improve their resilience in order to facilitate a faster recovery. Resilience can be viewed either as an outcome or as a process (Cutter 2016). It can be applied to multiple different scales and units of analysis, ranging from the individual scale (e.g person, building, etc.) to the global scale (e.g. community, state, etc.). The concept of resilience is multi-dimensional, and therefore involves various subjects of different disciplines (Bonstrom and Corotis 2014; Chang et al. 2014; Cimellaro et al. (2016a-b) . Resilience is defined as "the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways to minimize social disruption and mitigate the effects of further earthquakes" (Bruneau et al. 2003; Cimellaro et al. 2010). Allenby and Fink (2005) defined resilience as "the capability of a system to stay in a functional state and to degrade gracefully in the face of internal and external changes". In engineering, resilience is the ability to "withstand stress, survive, adapt, and bounce back from a crisis or disaster and rapidly move on" (Wagner and Breil 2013). Other researchers have also tackled other disciplines linked to resilience and proposed a more inclusive definition in relation to risk and uncertainty. For example, Ayyub (2015) suggested that "the resilience of a system is the persistence of its functions and performances under uncertainty in the face of disturbances". From the several definitions provided above, it is clear that it is still difficult to find a generally accepted definition for engineering resilience, mainly because this concept has only recently been applied in the engineering field.

Measuring resilience has been an exploding field of inquiry in the last decade. Bruneau et al. (2003) stated that the resilience of a system depends on its serviceability performance. In this conceptual approach, the performance of any system can range between 0% and 100%, where 100% indicates 'no drop in service' and 0% means 'no service is available'. Disastrous events usually cause the serviceability of a system to drop to a lower level. The restoration of the system starts immediately after the disaster and it finishes when the serviceability reaches its initial state (see Fig. 1). The loss of resilience is thought to be equal to the service degradation of the system over the whole restoration period. Mathematically, it is defined as follows:

$$LOR = \int_{t_0}^{t_1} \left[100 - Q(t)\right] dt \tag{1}$$

where LOR is the loss-in-resilience measure, t_0 is the time at which a disastrous event occurs, t_1 is the time at which the system recovers to 100% of its initial serviceability, $Q(t)$ is the serviceability of the system at a given time t.

Fig. 1 near here

Many options for measuring resilience ranging from specific measurements to scorecards to indices are available (Cimellaro et al. 2014; 2015) . Liu et al. (2017) proposed a framework that combines dynamic modeling with resilience analysis. Two interconnected critical infrastructures have been analyzed using the framework by performing a numerical calculation of the resilience conditions in terms of design, operation, and control parameters values for given failure scenarios. Cimellaro et al. (2016c; 2017) proposed a resilience index for water distribution networks that is the product of three indices and they used to compare different restoration plans in a small town in the South of Italy. Ayyub (2015) proposed simplified resilience metrics to meet logically consistent requirements drawn from measure theory. In his work, the recovery process, with its classifications based on level, spatial, and temporal considerations has also been tackled. More specific work has been done regarding the economic advantage of actions that boost a system's resilience (Gilbert and Ayyub 2016). In that work, microeconomic models that enable improving the resiliency of systems to meet target levels were introduced. Reviewing the available measurements allows distinguishing some features that separate them. Some are related to top-down measurement schemes, others are bottom-up, some measurements schemes are purely qualitative in their approach, and others are quantitative. These measurement systems are also spatialy variable and they differ in their focus and application. Some of the many existing top-down approaches include the PEOPLES framework (Cimellaro 2016b). The acronym combines seven dimensions: **P**opulation; **E**nvironment; **O**rganized government services; **P**hysical infrastructure; **L**ifestyle; **E**conomic; and **S**ocial capital. It is classified as a quantitative framework for designing and measuring resilience of communities. Another measurement tool is the Baseline Resilience Indicator for communities (BRIC) (Cutter et al. 2014). This measurement tool is also quantitative but it focuses on the pre-existing resilience of communities. Unlike the PEOPLES framework, BRIC is practically oriented towards the fieldwork. San Francisco Planning and Urban Research Association framework (SPUR) (SPUR 2009) is a qualitative framework that measures the ability to recover from earthquakes. The framework considers the restoration of buildings, infrastructures, and services. Other top-down approaches are: the Hyogo Framework for Action (HFA) (UNISDR 2005); the UK Department for International Development (DFID) Interagency Group (Twigg 2009); ResilUS (Miles and Chang 2011); etc. There are also few bottom-up approaches, which are usually designed for communities to help them predict and plan for resilience. These bottom-up measurement tools take an all-hazards approach in their assessment. They are generally qualitative types of assessments that the community does itself, or it works with local stakeholders to derive its assessment. Some bottom-up approaches include: the Conjoint Community Resiliency Assessment Measure (CCRAM) (Cohen et al. 2013), the Communities Advancing Resilience Toolkit (CART) (Pfefferbaum et al. 2011), the Community Resilient System (White et al. 2015), etc. A more exhaustive list of resilience measurement tools classified according to several characteristics can be found in (Cutter 2016).

The absence of a concise and methodological approach makes resilience extremely difficult to determine. The progress in the Hyogo Framework for Action (HFA) (UNISDR 2005; 2011)— a work developed by the United Nations — has led to the formulation of an international blueprint that is very useful for building the resilience of nations and communities. The methodology adopted by the HFA focuses on implementing detailed measures at the governmental level through policies. The goal is to encourage the countries to implement the HFA in their respective laws. The lifespan for the implementation was from 2005 to 2015, after which each of the participating countries was required to submit a report on their own progress. A score was then given by the UN to each of the submitted reports on the basis of the progress each country had made. Using the results of the Hyogo framework, a quantitative method to assess the resilience and the resilience based risk of countries is proposed and applied to a case study composed of 37 countries.

VULNERABILITY AND RESILIENCE ANALYSIS

One of the many topics discussed when referring to resilience is its relationship with vulnerability and whether they are similar enough to be considered the same. Vulnerability is an elusive concept whose definition varies across disciplines, ranging from engineering to economics to psycology. Despite the range of approaches to measuring vulnerability, several best practices in vulnerability assessment emerge. For instance, Peng et al. (2016) have developed an engineering-based damage assessment models to assess the vulnerability of low-rise buildings against tornadoes. The models can be implemented in any region regardless of the tornado size and strength. The output of this model is a percentage damage index and the overall building damage ratio. One of the most adopted tools for vulnerability and risk assessment is HAZUS. HAZUS is a standarized risk assessment software developed by the US Federal Emergency Management Agency (FEMA, fema.gov/hazus) for evaluating potential losses caused by natural hazards (Nastev and Todorov 2013). HAZUS integrates engineering and science-based knowledge with the geographic information systems (GIS) to determine the loss and damage before or after a disaster occurs. It consists of four main models:

1. The Hazus earthquake model: provides loss estimates of buildings, facilities, transportation, and utility lifelines based on scenario earthquakes to support decision making process for preparedness and disaster response planning (Whitman et al. 1997). The model considers debris generation, fire-following, casualties and shelter requirements. Direct losses are estimated based on physical damage to structures, contents, inventory and building interiors. The Hazus earthquake framework consists of six interdependent modules with the output of one module acting as input to another. More information about the framework algorithm and the modules can be found in (Kircher et al. 2006). In addition, a new extension module "*Advance Engineering Building Module*" (AEBM) has been integrated in the Hazus earthquake model to help seismic engineering experts in the development of building-specific damage and loss functions (NIBS 2002).
2. The Hazus Hurricane Wind Model: allows estimating hurrican winds and damage to different types of buildings. It also estimates direct economic loss, post-storm shelter needs and building and tree debris quantities and allows assessing the structural changes to buildings to strengthen them for mitigation. This model has been initially developed using principles of wind engineering to allow accurately estimating damage and loss to buildings due to hurricanes (Vickery et al. 2006a). The approach adopted in this model has been previously calibrated and validated using simulations and field observations of the wind speeds over more than

140 locations (Vickery et al. 2000a; 2000b). The HAZUS-MH Hurricane Model comprises five model components (hurricane hazard, terrain, wind Load/debris Modeling, damage, and loss Estimation). The first three components are described in (Vickery et al. 2006a) while the last two are discussed in a companion paper (Vickery et al. 2006b).

3. The Hazus Flood Model: evaluates potential damage to buildings, essential facilities, transportation lifelines, utility lifelines, vehicles and agricultural crops caused by riverine and coastal flooding. The model also considers building debris generation and shelter requirements. Direct losses are estimated based on physical damage to structures and to buildings' contents and interiors. Scawthorn et al. (2006a) provide a discussion of the capability of the software in characterizing riverine and coastal flooding. They also discuss the Flood Information Tool, which allows a quick and convenient analysis of various stream discharge data and topographic mapping to determine flood-frequencies over entire floodplains (Scawthorn et al. 2006a). In a companion paper, Scawthorn et al. (2006b) tackle the damage and loss estimation capability of the flood model. The model contains over 900 damage curves to estimate the damage of different tupes of buildings and infrastructures.
4. The Hazus Tsunami Model: represents the most recent disaster module for the Hazus software in the last decade. The model is a joint effort of tsunami experts, engineers, modelers, emergency planners, economists, social scientists, geographic information system (GIS) analysts, and software developers. New features are continouly added to this model in attempt to incease its capabilities.

Although vulnerability is strongly linked to the concept of risk assessment (Papadopoulos 2016), it has been pointed out that the concept of vulnerability is associated with resilience under various scientific disciplines (Richard et al. 1998). Meanwhile, vulnerability has been identified as the lack of capacity (Cardon et al. 2012). Under this context, the vulnerability is reduced by increasing the system's capacity. Moreover, some literary publications provide the same definitions for resilience and vulnerability (Klein et al. 2003), while others identified some instances where scholars had different views for the two concepts (Cutter 2016), admitting that they may overlap in some areas (Gallopín 2006). Table 1 shows a comparison between vulnerability and resilience on different scales. The comparison suggests that resilience is concerned more with the human capacity to recover from a disaster within a short time and with no outside assistance, while vulnerability is the property of resisting the stress caused by a natural hazard.

Table 1 near here

Due to the uncertainty involved in the resilience assessment process, a probabilistic approach similar to the classical vulnerability analysis can be established. Fig. 3 illustrates the conceptual approaches of both vulnerability and resilience analyses. In the vulnerability analysis, a number of fragility curves are built to interpret the vulnerability of a system. The curves represent the system's probability of exceeding a certain damage state under different hazard intensity levels. In the proposed resilience analysis, the fragility curves describe the probability of a system to be below a predefined resilience threshold under a certain intensity level (see Fig. 3).

It is important to note that the resilience quantity is affected by both the restoration period T_{re} and the rapidity of restoration r (see Fig. 1). Therefore, both quantities should be taken into account when estimating resilience. Fig. 3 shows the surface fragility curves when considering both intensity measures. Those curves represent the probability of a system having a certain recovery speed and a certain restoration period to be below a predefined resilience threshold.

Fig. 3 near here

The restoration speed (or rapidity) is one of the most important parameters when evaluating resilience. Generally, the rapidity of restoration r depends on several factors, such as the human resources, the restoration plan, the financial resources, etc. Thus, the graphical configuration of the restoration phase can be of infinite shapes. Fig. 4 shows three types of restoration curves (exponential function, step function, and random function). The rapidity of restoration r can be considered as the slope of the best-fitting line obtained by applying a linear regression to the restoration curve. In this way, r can express the rapidity of any restoration curve regardless of its actual configuration.

Fig. 4 near here

RESILIENCE-BASED RISK ANALYSIS

In the classical risk assessment methodology, Risk is the combination of Vulnerability, Hazard, and Exposure. Instead, in the proposed formulation, Resilience-Based Risk is a function of Resilience, Hazard, and Exposure (Fig. 2). While the three parameters can be obtained from various sources, for the specific case study considered in this research, the exposure is obtained from the World Risk Report (WRR), while the effect of hazard is neglected due to the lack of the necessary hazard maps. The third parameter, resilience, is determined using the data provided by the Hyogo Framework for Action (HFA). HFA ranks and scores countries based on a number of equally weighted indicators. However, in order to be used in the resilience assessment, the HFA indicators must be weighted according to their contribution toward resilience. To do that, three weighting methods are introduced. The first two methods are based on the Dependence Tree Analysis (DTA) (Kammouh et al. 2016a; Kammouh et al. 2016b). DTA is a method that determines the correlation between a component and its sub-components (i.e., between resilience and its indicators), assigning different weights to the sub-components accordingly. The third method, Spider Plot Analysis (SPA), is based on a geometrical combination of the indicators using spider plots. In this method, the score of each indicator is plotted on one of the spider plot's axes. Resilience is then quantified as normalized value of the area inside the enclosed shape made by linking the adjacent indicators' scores. The outputs of the resilience generated by each of the three methods are subsequently used in the evaluation of RBR (by combining them with exposure and hazard). To illustrate the use of the methodology, a case study composed of 37 countries is presented in this paper, where the resilience and the resilience-based risk indexes of each country are evaluated and compared.

Fig. 2 near here

THE WORLD RISK REPORT (WRR)

The World Risk Report is a research performed by the United Nations University for Environment and Human Security (UNU-EHS), and published by the relief organizations in the Alliance Development Works (Mucke 2015). The report adopts different measures to rank the countries around the world according to their vulnerability, exposure, and risk levels. In this study, the data on exposure level of the WRR is used for the resilience-based risk assessment. The strategy adopted by the WRR to evaluate the exposure of the countries is illustrated in Fig. 5. The exposure is computed as a combination between the people who are exposed to different types of hazards in a country divided over the total population in that country. Fig. 6 shows the exposure values of the ten most exposed countries according to the WRR.

Fig. 5 near here

Fig. 6 near here

HYOGO FRAMEWORK FOR ACTION (HFA)

Hyogo Framework for Action (HFA) was originally conceptualized in Kobe, Japan. It was eventually adopted as a global blueprint for minimizing risk associated with natural hazards by implementing national laws regarding risk management and control (UNISDR 2005; UNISDR 2011). HFA is the product of a long initiative by an affiliate within the United Nations known as the International Strategy of Disaster Reduction (ISDR) (Cimellaro 2016). The International Strategy of Disaster Reduction was developed as the result of the experience gained in the International Decade for Natural Disaster Reduction (1990-1999).

The aim of HFA was to boost awareness on disaster risk and to guide committed countries in executing a master plan to avert the loss of lives and the economic impact caused by natural hazards. The HFA consists of five priorities for action. Each priority is satisfied with a number of indicators, with a total of 22 indicators for all five priorities (Table 2). The major role of the five priorities of HFA is to identify the specific sectors that every country should focus on to endorse disaster resilience. The indicators are assessed using a detailed survey, which contains a set of questions that aim to provide information about the resilience progress each country has made. The authority of each country is requested to fill the questionnaire and then return it to the UN for further processing. Table 3 shows the sort of questions presented in the questionnaire. The answers to the questions can be either ‘YES/NO’ or ‘description text’. The progress recorded by every government is computed on the basis of a five-point scale for each of indicator, where 'one point' indicates weak progress and poor signs of planning and actions, while 'five points' implies a great endeavor and commitment in that specific area (UNISDR 2008).

The level of accuracy of the data collected by the UN is subjected to the authority personnel who fills the report. However, the authorities of the countries are aware that providing a good quality data allows them to track their resilience progress more accurately.

Table 2 near here

The expiration of Hyogo and its ten-year plan prompted a new framework known as Sendai Framework. This framework is the evolved version of the HFA and is meant to replace HFA in coming years. The Sendai Framework is a product of the Third World Conference on Disaster Risk Reduction in Sendai, Japan (2015) (UNISDR 2015). Even though the HFA was widely credited as raising awareness for disaster risk reduction, a significant loss of lives was recorded during the 10-year span of its implementation. Consequently, the Sendai framework stresses on the significance of risk assessment and early warning systems. The UN have set a plan to define the risk bases and to embrace new indicators to quantify the resilience improvement made by the participating countries, and this is anticipated to be discussed at another session in 2017 (UNISDR 2015). The new framework outlines the following four priorities for action:

1. Understanding disaster risk;
2. Strengthening disaster risk governance to manage disaster risk;
3. Investing in disaster risk reduction for resilience;
4. Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction.

Table 3 near here

THE METHODOLOGY: RESILIENCE-BASED RISK ASSESSMENT OF COUNTRIES

The primary goal of the paper is to provide an index that enables comparing countries in terms of resilience and its corresponding risk. In this work, risk is the probability of not achieving a certain resilience level, and is referred to as resilience-based risk. The RBR is dependent on not only the internal characteristics of a system (resilience) but also on the external factors (exposure and hazard). Fig. 7 illustrates the proposed framework, where risk is the combination of resilience, exposure and hazard. The mathematical expression of RBR is given by:

$$RBR = (1 - R) \times E \times H \tag{2}$$

where *RBR* is the resilience-based risk index, *R* represents the resilience index, *E* is the exposure to natural hazards, *H* contains information about the hazard. For the purpose of the study, we have chosen puclic data sources to illustrate the methodology. For example, to compute the resilience parameter, we used the data provided by the Hyogo Framework for Action, which uses a number between 0 and 1 to assess the different resilience indicators of the countries. As already indicated, the 22 indicators in HFA are equally weighted, and this implies that all indicators have the same level of importance. However, it has been found that the indicators vary in importance, and therefore they must be weighted in a specific way in order to be used in the resilience assessment. To do that, three different weighting methods are applied to the HFA indicators, and the corresponding resilience results are compared. In the following, the three weighting methods are explained in detail.

Fig. 7 near here

Method 1: Dependence Tree Analysis (DTA)

In this section, the Dependence Tree Analysis (DTA) is introduced. The method captures the correlation between a component and its sub-components in a quantitative manner. The DTA is applied to the HFA's indicators in order to combine them according to their contribution towards resilience. Building the dependence tree begins with the identification of all potential components that are capable of influencing the main output. The most common way to do this is by brainstorming or relating to lessons learned. The types of components that exist are: the main component, the intermediate component, and the basic component. The task required to get out of a system is known as the main component, and this component is located on the top of the dependence tree. The essential components required for the successful achievement of the main component are known as the intermediate components, while the basic components refer to those that cannot be split any further into sub-components. Fig. 8 illustrates how the components are arranged in the dependence tree. The components are presented in the dependence tree according to their logical relationship with one another. The components can show in the dependence tree more than once, and this depends on the importance of that component. In this work, resilience is considered as the main component, while the HFA's indicators are the intermediate and the basic components. Therefore, all sub-components will hereafter be referred to as indicators, while the main component will be referred to as resilience. The results obtained using the DTA are highly dependent on the tree structure which describes the links between the different indicators. Furthermore another limitation of the method is that only numerical indicators can be combined (e.g. boolean indicators can not be used with this methodology) .

Fig. 8 near here

The analysis begins with the identification of the indicators and their relationships. The indicators' scores obtained from HFA are normalized with respect to their maximum value (I_{max}=5) using Equation (3). Afterward, resilience is computed using the DTA by combining the indicators' scores in such a way that the indicators that are in series are multiplied, while the weighted average of those in parallel is considered. This leads to obtaining a normalized resilience output that is ranged between 0 and 1.

$$I_{iN} = \frac{I_i}{I_{i,\max}} \tag{3}$$

where $I_{i,N}$ is the normalized score of indicator i ($0 \le I_{i,N} \le 1$), I_i is the score of indicator i obtained from HFA ($0 \le I_i \le 5$), $I_{i,\,max}$ is the maximum score that can be achieved by indicator i ($I_{\max} = 5$).

Method 2: Weighted Average Analysis (WAA)

In this method, the dependence tree analysis is used only to find weighting factors for the indicators. Then, the resilience is evaluated as the weighted average of the indicators' weighted scores. The weights are obtained by performing a sensitivity analysis. This is done by setting the score of each indicator to zero once at a time while assigning maximum values to all other indicators. The value of the resilience is computed for each time an indicator is set to zero. A low value of resilience indicates a high importance of that indicator. Therefore, the importance factor of the indicator is the opposite of the resilience value when that indicator is set to zero. Equation (4) is used to compute the importance factors.

$$IF_i = 1 - R_i \qquad \text{for } I_{iN} = 0\,;\; I_{jN} = I_{j\,\max,N} = 1 \quad (i = 1 \rightarrow k \text{ and } j \ne i) \tag{4}$$

where IF_i is the importance factor of indicator i, R_i is the value of resilience when indicator i is set to zero while all other indicators are equal to 1, k is the total number of indicators (i.e. k =22).

The execution of the sensitivity analysis enables classifying the indicators starting from the most to the least important. A weighting factor for every indicator of the HFA is subsequently calculated using Equation (5). In this equation, the weighting factor uses the results of the sensitivity analysis conducted in the previous step.

$$W_i = \frac{1 - IF_i}{\sum_{n=1}^{k} (1 - IF_n)} \tag{5}$$

where W_i is the weighting factor of indicator i. The new indicator's score is obtained by multiplying the original indicator's normalized score by its corresponding weighting factor:

$$I_{i,NW} = W_i \cdot I_{i,N} \tag{6}$$

where $I_{i,NW}$ is the normalized weighted score of indicator i.

Finally, the resilience value R is the weighted average of the indicators' modified scores. The mathematical equation of resilience is given as follows:

$$R = \sum_{n=1}^{k} I_{n,NW} \quad (7)$$

Method 3: Spider Plot Weighted Area Analysis (SPA)

In this last method, the indicators are represented by means of a spider plot (Fig. 9). Resilience is simply the enclosed area generated by linking the adjacent indicators, normalized with respect to the total area of the polygon. The mathematical expression of resilience is given in Equation (8). One can say that the arrangement of indicators could affect the area in the enclosed shape. To illustrate this, a statistical analysis was performed on the indicators' scores of one country. Different arrangements of the indicators were tried using the permutation command in the software Matlab (Guide 1998), and the area of each arrangement was computed. It was found that the values of the areas were normally distributed with a standard deviation of 5%. This implies that the value of the area inside the enclosed shape is not very sensitive to the indicators' arrangement order.

$$R = \frac{A}{A_{\max}} \quad (8)$$

where R is the resilience index, A is the area of the geometrical shape obtained by connecting the scores of adjacent indicators, A_{max} is the total area of the polygon (i.e. maximum area that could be achieved if all indicators are equal to 5).

Fig. 9 near here

THE CASE STUDY

The methodology described in the paper has been applied to a number of countries that took part in the Hyogo Framework evaluation project. The chosen countries are 37 in total, and they were selected randomly from all five continents. For each country, the resilience index R is evaluated, and then the corresponding risk index RBR is computed by combining the results of resilience, exposure, and hazard.

In Table 4, the indicators' scores of the various countries are listed as presented in the HFA reports. The latest reports to date are used to fill the scores. The indicators' scores of each country are summed up into a single total score (out of 110 points). This score is also presented in percentage form (%), where 100 indicates a maximum score of 5 in all indicators. The final set of total scores act as a data source for the proposed methodology.

Table 4 near here

Resilience results

In this section, the resilience indexes of the analyzed countries are computed using the proposed methods and then compared.

Method 1: Dependence Tree Analysis (DTA) results

Fig. 10 shows the final form of the dependence tree, in which all the indicators have been arranged according to their logical relationship with one another. One indicator can take more than one place, and this depends on how significant the indicator is.

Fig. 10 near here

As we mentioned before, the 22 indicators' scores of each country (obtained from HFA) are normalized with respect to their maximum value. The maximum value that can be achieved by an indicator is "5"; therefore, all indicators are divided over five. Once the indicators are normalized, the resilience index of each country is computed by combining the indicators' scores. In the dependence tree, the indicators in series are multiplied by each other, whereas averaging was taken for those indicators in parallel. The resilience index of each country can be obtained by replacing each indicator with its corresponding normalized score value from Eq. (3). The general formula to compute the resilience *Rc* of a country *c* is given Eq. (9). Using the equation, the resilience results of the analyzed countries can be computed.

$$R_c = \frac{1}{10}\left[\begin{array}{l} I_{13N} I_{1N} I_{9N} I_{2N} + I_{14N}\left(\dfrac{I_{1N} I_{9N} I_{2N} + I_{3N}\left(\dfrac{I_{9N} I_{2N} + I_{10N} I_{2N} + I_{12N} I_{2N}}{3}\right)}{2}\right) + I_{15N}\left(\dfrac{I_{1N} I_{9N} I_{2N} + I_{4N} + I_{6N} I_{1N} I_{9N} I_{2N}}{3}\right) \\ + I_{16N}\left(\dfrac{I_{1N} I_{9N} I_{2N} + I_{9N} I_{2N}}{2}\right) + I_{17N}\left(\dfrac{I_{5N} I_{9N} I_{2N} + I_{4N}}{2}\right) + I_{18N}\left(\dfrac{I_{1N} I_{9N} I_{2N} + I_{4N} + I_{5N} I_{9N} I_{2N} + I_{8N}}{4}\right) \\ + I_{19N}\left(\dfrac{I_{1N} I_{9N} I_{2N} + I_{2N} + I_{4N} + I_{5N} I_{9N} I_{2N}}{4}\right) + I_{20N}\left(\dfrac{I_{6N} I_{1N} I_{9N} I_{2N} + I_{7N} I_{2N}}{2}\right) + I_{21N}\left(\dfrac{I_{1N} I_{9N} I_{2N} + I_{11N} I_{2N}}{2}\right) \\ + I_{22N} I_{1N} I_{9N} I_{2N} \end{array}\right] \quad (9)$$

Method 2: Weighted Average Analysis (WAA) results

In this method, the Dependence Tree Analysis (DTA) is used to weight the indicators shown in Table 2. A sensitivity analysis is performed to capture the difference in the indicators' contribution in the resilience assessment. This leads to assigning a single weighting factor to each of the 22 indicators. Following the procedure described above, and by using Equations (4) and (5), a list of importance and weighting factors for the 22 indicators is generated (Table 5). We can clearly notice the difference in the indicators' weights. For instance, indicator 2 (I-2) recorded the highest weighting factor '0.225'. In fact, this indicator 'Dedicated and adequate resources are available to implement disaster risk reduction plans and activities at all administrative levels' is a financial indicator, and almost all other indicators were dependent on it in the dependence tree (Fig. 10). Generally, financial indicators are very important because financial resources are necessary for the accomplishment of any task, and this justifies the high weighting factor obtained by that indicator.

Table 5 near here

The weighting factors shown in the table above are multiplied by the corresponding indicators' normalized scores using Equation (6). The new 22 indicators' scores are subsequently summed up using Equation (7). The result obtained represents the resilience index *Rc* of the country *c*.

Method 3: Spider Plot Weighted Area Analysis (SPA) results

The indicators' spider chart of each country is plotted and the area inside the enclosed shape made by linking the adjacent indicators' scores is obtained. Fig. 11 shows two examples of the spider plot method corresponding to the countries France and Monaco. Using Equation (8), The resilience index *Rc* of a country *c* is obtained by normalizing the area inside the enclosed shape A_c with respect to the maximum area $A_{c,max}$ (i.e. the maximum area is obtained when all indicators are maximum '5').

Fig. 11 near here

Fig. 12 compares the results of the resilience obtained with the three methods. Interestingly, the results coming from all three methods follow the same trend. The third method (SPA) acts as an average for the first (DTA) and the second (WWA) methods, except for Fiji country, which acquired equal scores in the second and third methods, slightly higher than the score obtained from the first method. All together, these results suggest that the resilience outputs are very sensitive to the weighting method. The first method (DTA) provides the highest difference between the largest and the lowest scores, whereas the variability in the results obtained using the second method (WWA) is the lowest, with a difference of 0.58 between the highest value (0.98) and the lowest value (0.4). This can be considered in the favor of the first method as it magnifies the range of the resilience results, which allows having a clearer picture on the difference in resilience between countries. In addition, the first method (DTA) does not allow very high values of resilience; for instance, the highest resilience score achieved using the DTA method is that of the Fiji country (R=0.84). This assumes that there is no country that is considered fully resilient, and this is a more reasonable result than in the other two methods where the resilience index of Fiji is 0.98, which implies that Fiji can hardly get any better in terms of resilience.

Moreover, the resilience results shows that Fiji has always achieved the first position in the resilience ranking, which is rather unexpected. This may be attributed to several reasons, such as the subjectivity in filling the HFA reports in the first place. Fiji has initially achieved a score of 109 out of 110 in the HFA evaluation (Table 4), which implies that whatever weighting strategy was adopted, it would still be ineffective in changing the ranking of Fiji. Nevertheless, this does not affect the validity of the Hyogo framework data as there is absolutely no benefit for any country to provide fake data and information. In addition, the results obtained in this study are to give an indication on how well each country is doing in terms of resilience. The results can be used for comparing the countries rather than knowing their actual resilience. The actual resilience of the country may vary significantly inside the country itself; therefore, we do not intent to provide exhaustic resilience values for the countries, which is absolutely not feasible considering the complexity involved in the process.

Fig. 12 near here

Resilience-Based Risk results

In this framework, the last step is to quantify the resilience-based risk index (RBR). As already indicated, the risk index is the combination between resilience, exposure, and hazard. For the sake of this example, the hazard is assumed to be '1' in an attempt to disregard its effect. Therefore, in this specific case study, the risk index is presented in terms of the hazard parameter, which upon availibility it can be combined directly with the results obtained in this study. The table below shows the resilience results derived using the three methods and the exposure of every country obtained from the WRR. The resilience-based risk index of every country is subsequently computed using Equation (2).

Table 6 near here

The numerical results obtained by combining resilience (Fig. 12) with exposure (Fig. 13) using Equation (2) are presented in Fig. 14. It is clear that the risk and the resilience results are far from proportional, and this supports the notion that the most prepared countries (i.e. having high resilience) do not necessarily have the lowest risk. For instance, Japan is widely known for its high preparedness level against natural disasters. Although it is classified among the 'best' countries in the resilience ranking (Fig. 12), Japan is placed among the countries with the highest risk (Fig. 14), and this is because Japan is highly exposed to disasters (Fig. 13). Therefore, the resilience by itself is not a good indicator of the probability of being under a certain resilience level, because the process depends also on the exposure level.

Fig. 13 near here

Fig. 14 near here

CONCLUSIONS

Resilience measurements are important tools for communities to understand the benefit cost of implementing resilience actions and to evaluate the effects of these actions by looking at different policies and approaches. They can give an idea on where additional resources should be allocated. Although these measurment tools cannot create resilient communities, they can certainly help show and illustrate a path that the community can take to become safer and stronger and more vibrant in the face of unanticipated events.

This paper presents a new analytical approach for calculating the resilience and the resilience-based risk of countries. The resilience-based risk is defined as the probability of being below a certain resilience threshold, and is computed by combining resilience, exposure, and hazard. In this paper, the resilience parameter is evaluated using the results of Hyogo

Framework for Action, which ranks the countries based on 22 indicators. The indicators of the HFA are combined using three different methods to determine the resilience index. The first two methods are based on the Dependence Tree Analysis. DTA is a method that identifies the correlation between resilience and its indicators in a quantitative manner, giving weighting factors the indicators accordingly. The third method is a geometrical method in which the indicators' scores are plotted on the spider chart' axes. The resilience is quantified as a normalized value of the area inside the enclosed shape made by linking the adjacent indicators' scores.

The applicability of the proposed methodology has been tested on 37 countries by calculating their respective resilience and risk indexes. Although the results obtained from the three methods are proportional, the sensitivity on the resilience results provided by each method is different. The first method (DTA) is preferred with respect to the other two because it amplifies the score range of the resilience results of the countries. Then, the resilience-based risk index *RBR* for each country is computed. The obtained numerical results show that the risk of being below a certain resilience threshold depends greatly on the exposure level of that country.

In conclusion, in the paper a specific data set collected by United Nation has been used to illustrate the methodology. However, the proposed approach is general and it can be applied using more reliable data as soon as they are available, such as the data that will be provided in the "Sendai Framework".

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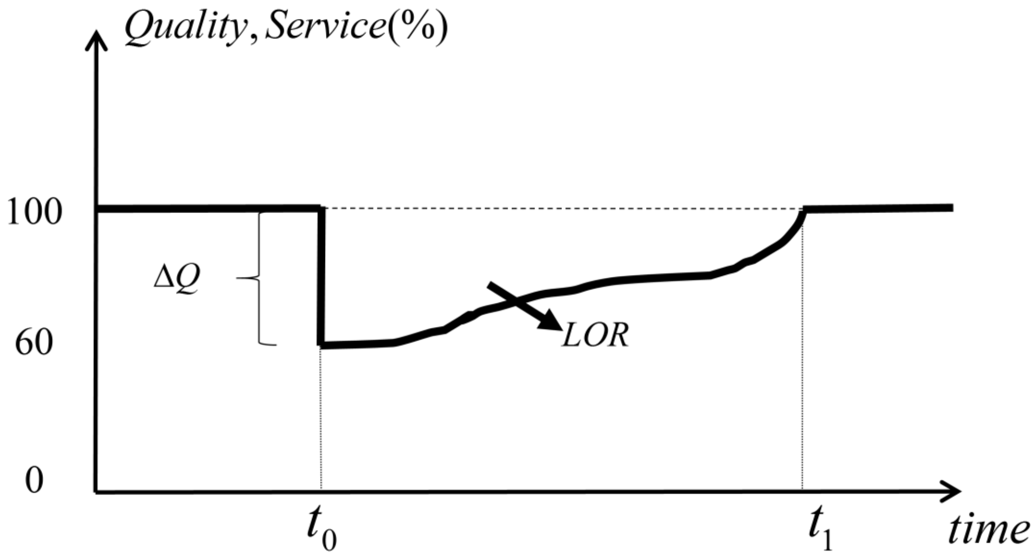
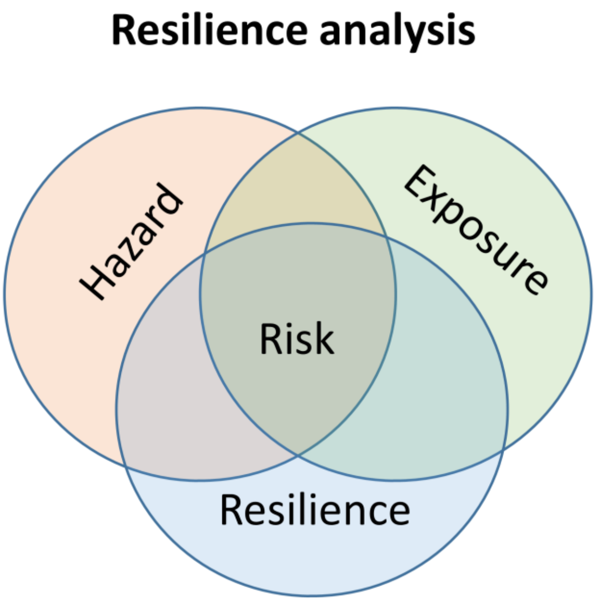
- Fig. 1 A conceptual representation of engineering resilience

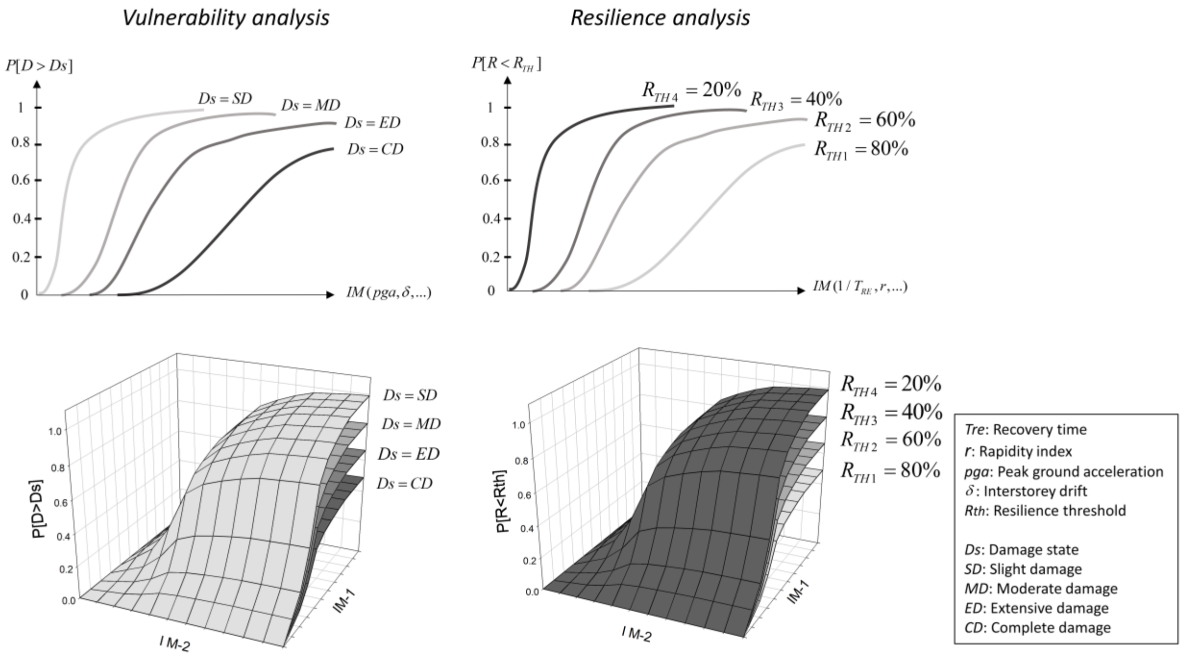


- Fig. 2 Resilience-based risk analysis Venn diagram

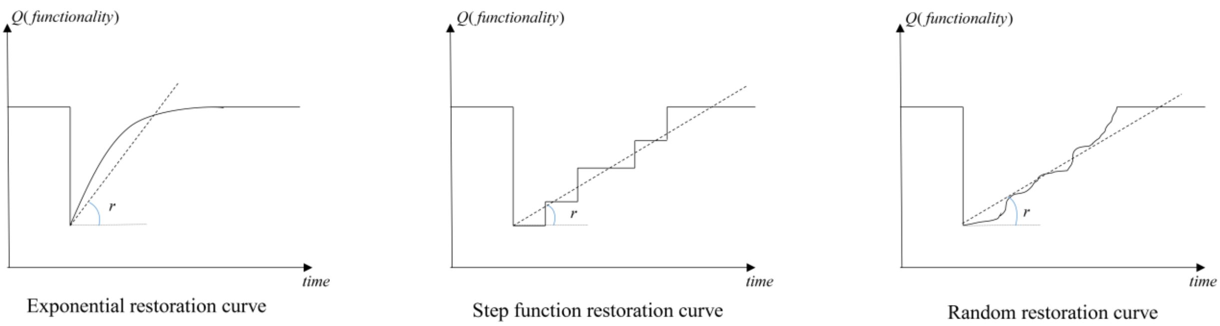


$$Risk = R \times E \times H$$

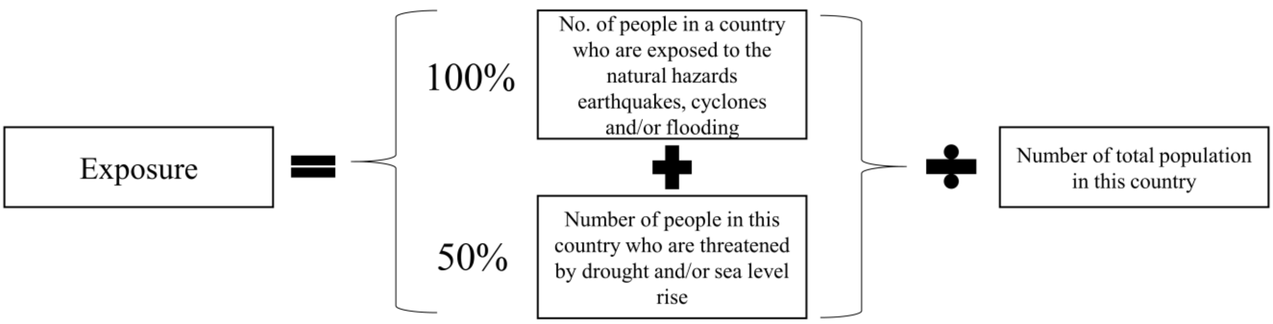
- Fig. 3 Comparison between the vulnerability and the resilience analyses



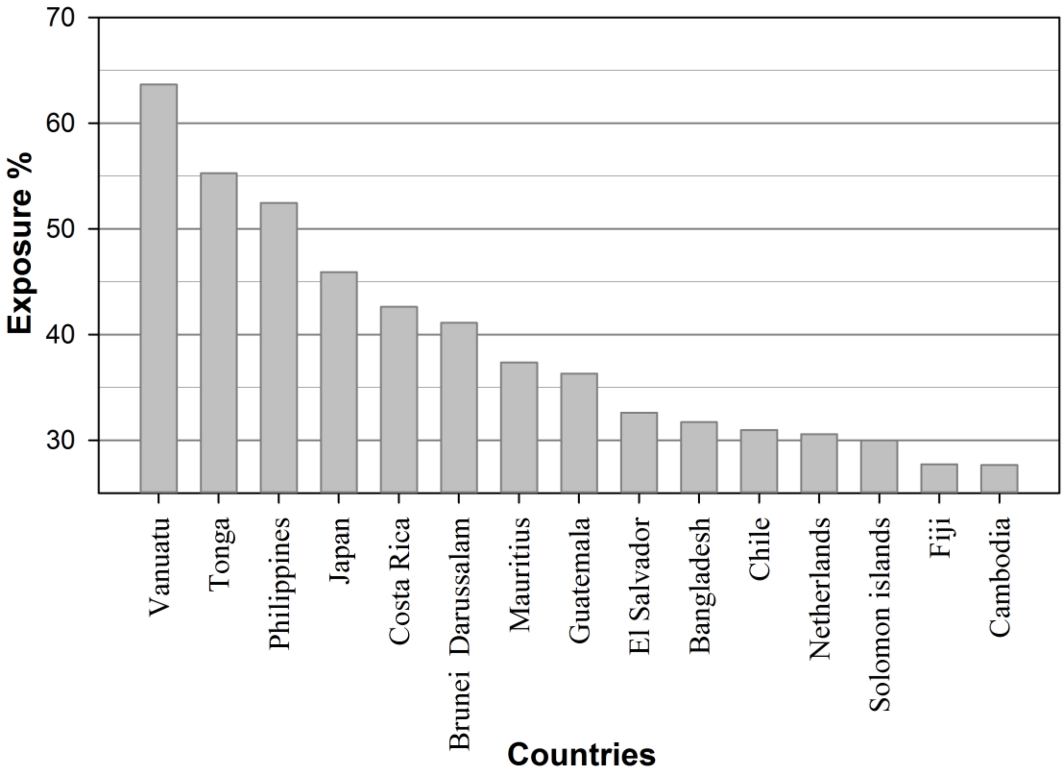
- Fig. 4 Typical restoration models



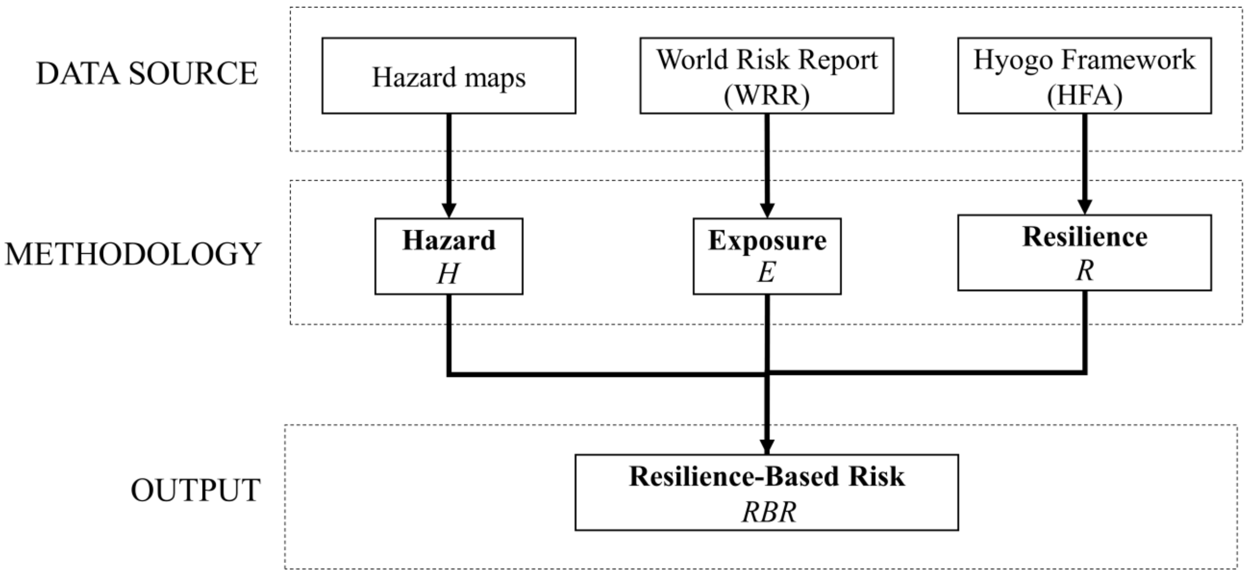
- Fig. 5 Exposure analysis in the World Risk Report



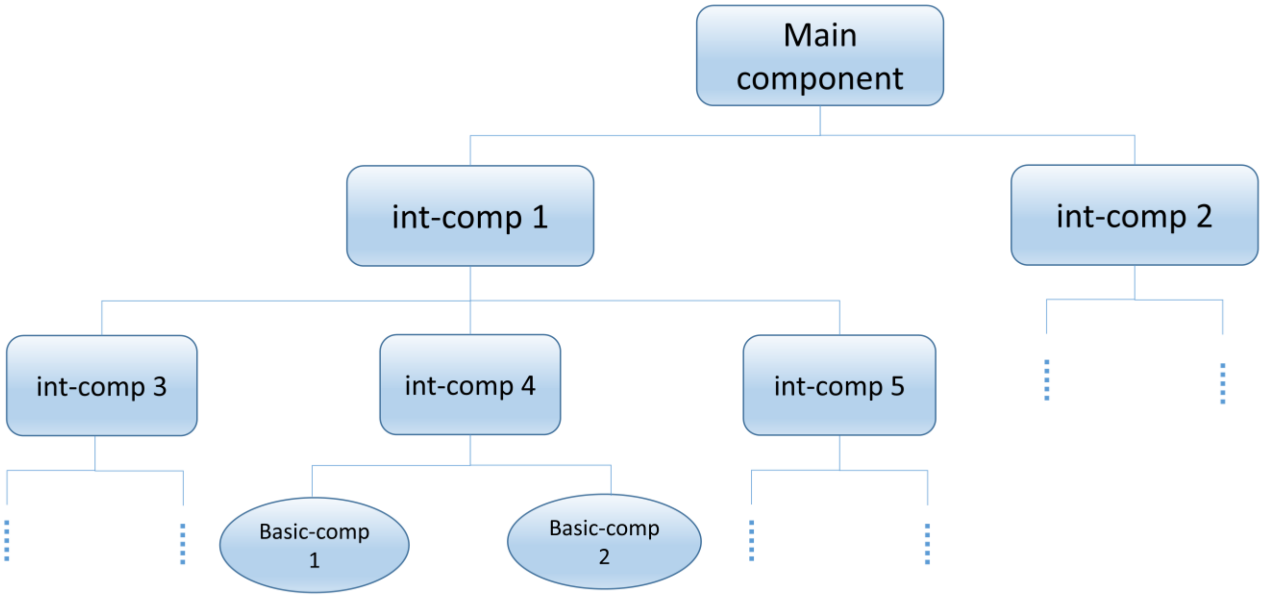
- Fig. 6 The ten most exposed countries according to the WRR



- Fig. 7 Framework of the proposed methodology



551 • Fig. 8 A dependence tree diagram showing the different types of components



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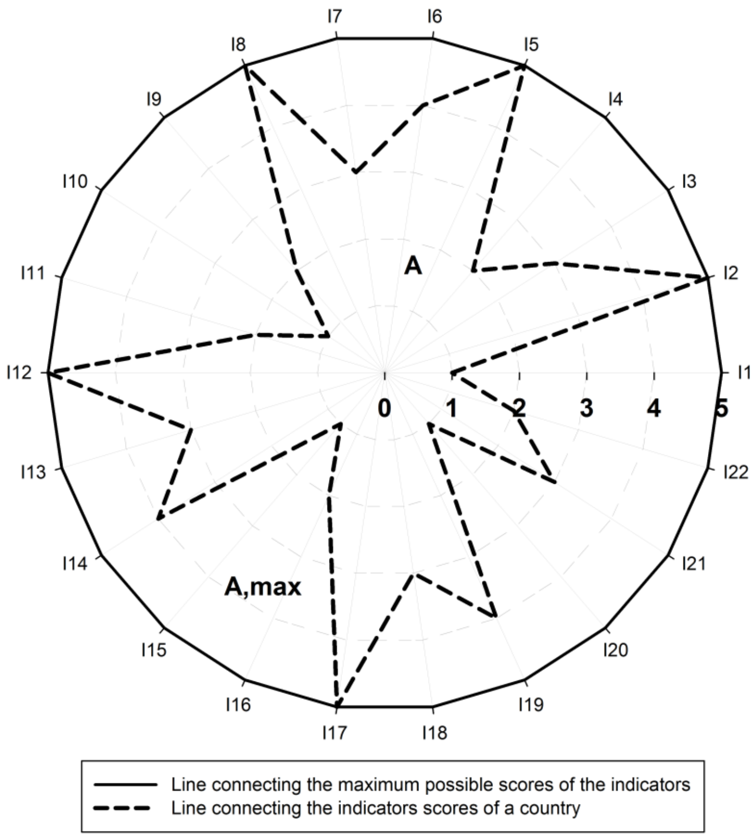
554 • Fig. 9 Spider plot representation of the HFA indicators scores



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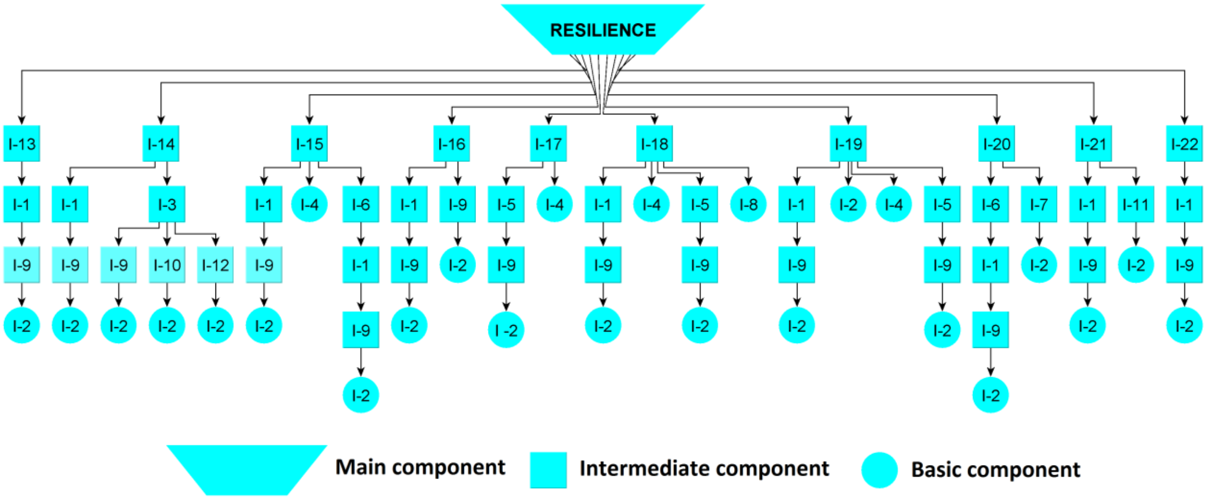
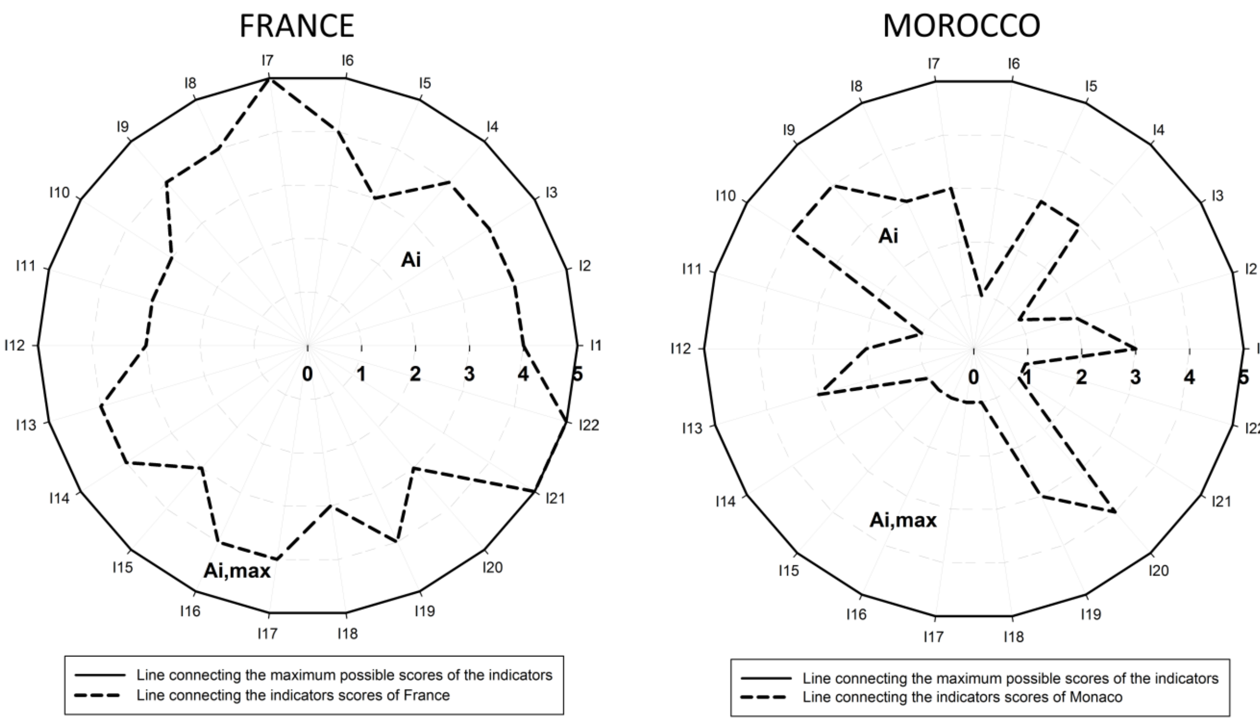
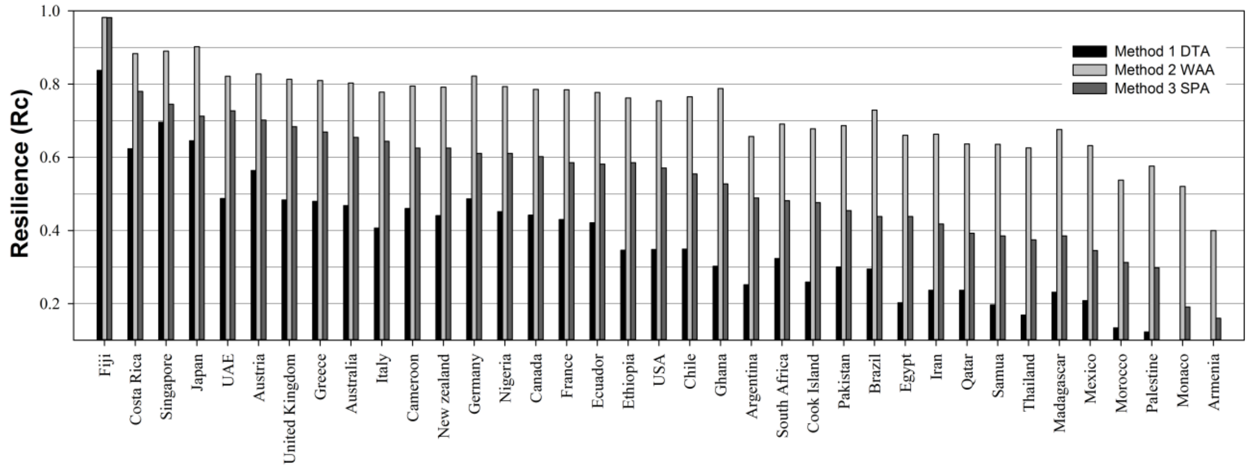
- Fig. 10 The dependence tree of the HFA's indicators



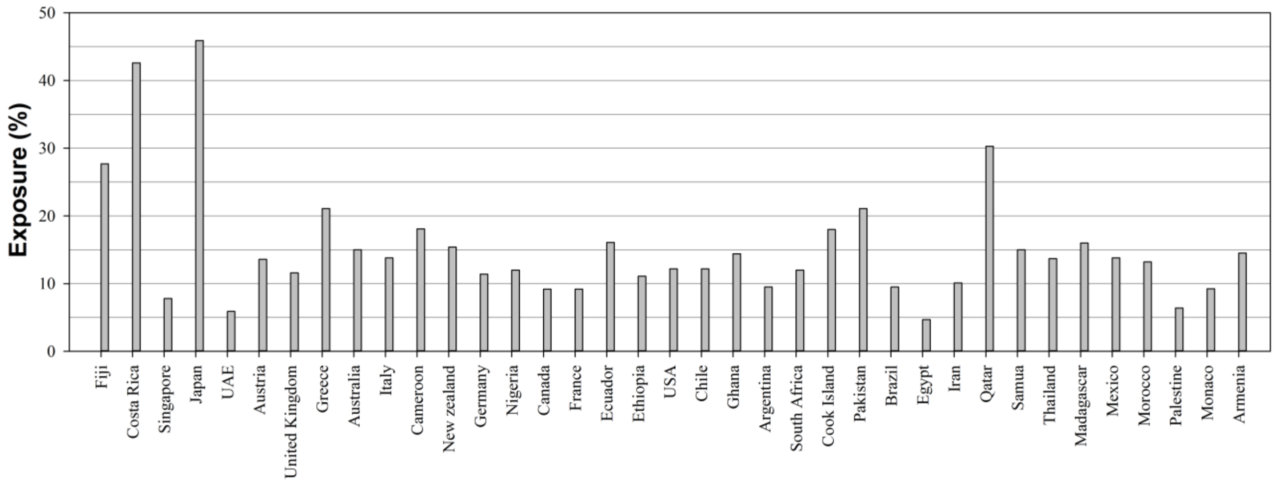
- Fig. 11 Examples of the spider plot method for two countries (France and Monaco)



- Fig. 12 Resilience results obtained by the three methods



- Fig. 13 Exposure results of the studied countries obtained from the WRR



- Fig. 14 Risk results obtained using the results of resilience obtained by the three method

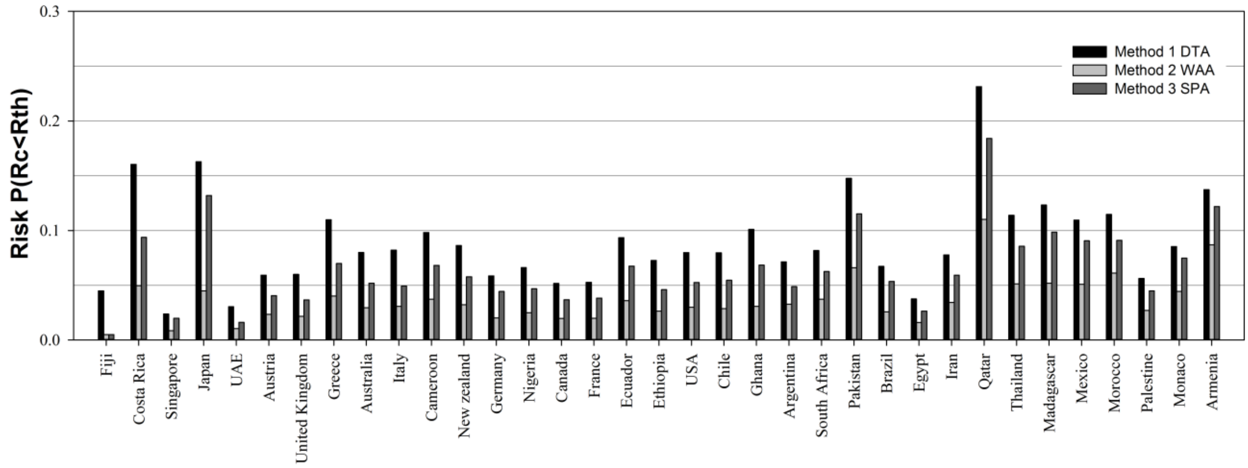


Table 1. Difference between vulnerability and resilience at different levels. Adapted from (Cimellaro 2016a)

Vulnerability	**Resilience**
Resistance	Recovery
Force bound	Time bound
Safety	Bounce back
Mitigation	Adaptation
Institutional	Community-based
System	Network
Engineering	Culture
Risk assessment	Vulnerability and capacity analysis
Outcome	Process
Standards	Institution

Table 2. Priorities and indicators used in the assessment of Hyogo Framework for Action. Adapted from (UNISDR 2011)

PRIORITY 1:
Ensure that disaster risk reduction (DRR) is a national and a local priority with a strong institutional basis for implementation

I 1	National policy and legal framework for disaster risk reduction exists with decentralized responsibilities and capacities at all levels.
I 2	Dedicated and adequate resources are available to implement disaster risk reduction plans and activities at all administrative levels
I 3	Community Participation and decentralization is ensured through the delegation of authority and resources to local levels
I 4	A national multi sectoral platform for disaster risk reduction is functioning.

PRIORITY 2:
Identify, assess and monitor disaster risks and enhance early warning

I 5	National and local risk assessments based on hazard data and vulnerability information are available and include risk assessments for key sectors.
I 6	Systems are in place to monitor, archive and disseminate data on key hazards and vulnerabilities
I 7	Early warning systems are in place for all major hazards, with outreach to communities.
I 8	National and local risk assessments take account of regional / trans boundary risks, with a view to regional cooperation on risk reduction.

PRIORITY 3:
Use knowledge, innovation, and education to build a culture of safety and resilience at all levels

I 9	Relevant information on disasters is available and accessible at all levels, to all stakeholders (through networks, development of information sharing systems etc.)
I 10	School curricula, education material and relevant trainings include disaster risk reduction and recovery concepts and practices.
I 11	Research methods and tools for multi-risk assessments and cost benefit analysis are developed and strengthened.
I 12	Countrywide public awareness strategy exists to stimulate a culture of disaster resilience, with outreach to urban and rural communities.

PRIORITY 4:
Reduce the underlying risk factors

I 13	Disaster risk reduction is an integral objective of environment related policies and plans, including for land use natural resource management and adaptation to climate change.
I 14	Social development policies and plans are being implemented to reduce the vulnerability of populations most at risk.
I 15	Economic and productive sectorial policies and plans have been implemented to reduce the vulnerability of economic activities
I 16	Planning and management of human settlements incorporate disaster risk reduction components, including enforcement of building codes.
I 17	Disaster risk reduction measures are integrated into post disaster recovery and rehabilitation processes
I 18	Procedures are in place to assess the disaster risk impacts of major development projects, especially infrastructure.

PRIORITY5:
Strengthen disaster preparedness for effective response at all levels

I 19	Strong policy, technical and institutional capacities and mechanisms for disaster risk management, with a disaster risk reduction perspective are in place.
I 20	Disaster preparedness plans and contingency plans are in place at all administrative levels, and regular training drills and rehearsals are held to test and develop disaster response programs.
I 21	Financial reserves and contingency mechanisms are in place to support effective response and recovery when required.
I 22	Procedures are in place to exchange relevant information during hazard events and disasters, and to undertake post-event reviews

Table 3. The questions asked by the UN to assess the first indicator. Adapted from (UNISDR 2011)

Indicator 1	**National policy and legal framework for disaster risk reduction exists with decentralized responsibilities and capacities at all levels.**	**Answer type**
Questions	-Is disaster risk taken into account in public investment and planning decisions?	YES/NO
	-National development plan	YES/NO
	-Sector strategies and plans	YES/NO
	-Climate change policy and strategy	YES/NO
	-Poverty reduction strategy papers	YES/NO
	-CCA/ UNDAF (Common Country Assessment/ UN Development Assistance Framework)	YES/NO
	-Civil defense policy, strategy and contingency planning	YES/NO
	-Have legislative and/or regulatory provisions been made for managing disaster risk?	YES/NO
	-Description	Write text
	-Context & Constraints	Write text
	Level of progress achieved: (1 to 5)	

Table 4. Indicators scores for the analyzed countries

Countries \ Indicators	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20	I21	I22	Total (per 110)	Total (%)
1-Fiji	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	109	99.1
2-Costa Rica	5	4	4	5	3	4	5	4	4	4	5	4	4	4	3	5	5	5	5	5	5	5	97	88.2
3-Singapore	5	5	5	2	5	5	5	5	5	5	5	5	2	5	5	4	1	1	5	5	4	5	94	85.5
4-Japan	5	4	4	5	4	4	4	4	5	4	3	5	4	4	4	4	4	5	5	4	4	4	93	84.5
5-UAE	5	4	5	4	4	4	3	3	3	4	4	5	5	5	5	5	5	5	4	4	3	4	93	84.5
6-Austria	4	5	5	3	4	4	5	5	4	4	3	4	4	4	4	4	4	5	5	4	4	4	92	83.6
7-UK	4	4	5	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	91	82.7
8-Greece	4	4	4	4	4	4	5	4	4	4	4	4	4	4	4	5	4	4	4	4	4	4	90	81.8
9-Australia	4	4	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	89	80.9
10-Italy	2	4	4	4	4	4	5	4	5	4	4	4	4	3	3	3	5	4	5	5	4	4	88	80.0
11-Cameroon	4	4	4	5	4	4	4	4	4	4	4	4	4	3	4	4	4	4	4	3	4	4	87	79.1
12-New Zealand	4	4	4	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	87	79.1
13-Germany	5	4	4	4	4	4	4	4	4	3	4	4	4	5	3	4	3	3	4	4	4	4	86	78.2
14-Nigeria	4	4	2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	86	78.2
15-Canada	4	4	5	4	3	4	4	4	4	3	3	4	3	3	4	4	5	4	5	5	3	3	85	77.3
16-France	4	4	4	4	3	4	5	4	4	3	3	3	4	4	3	4	4	3	4	3	5	5	84	76.4
17-Ecuador	4	4	4	4	3	4	3	4	4	4	4	4	4	4	4	4	4	3	4	4	3	4	84	76.4
18-Ethiopia	4	3	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	4	4	4	4	4	84	76.4
19-USA	4	4	4	3	4	4	4	4	3	4	4	4	3	3	3	4	4	4	4	4	4	4	83	75.5
20-Chile	4	3	3	4	4	3	4	3	4	4	2	4	3	4	4	4	4	4	4	4	5	4	82	74.5
21-Ghana	4	2	2	4	4	4	4	4	5	1	4	4	4	4	3	3	4	4	4	4	4	4	80	72.7
22-Argentina	3	3	4	4	4	3	4	4	3	3	3	4	3	3	3	4	4	4	4	4	2	4	77	70.0
23-South Africa	4	4	4	4	3	3	3	3	3	3	3	3	4	3	3	3	4	4	3	4	4	4	76	69.1
24-Cook Island	4	3	4	4	3	4	4	4	3	3	3	4	4	3	3	3	4	3	4	3	3	3	76	69.1
25-Pakistan	4	4	4	4	3	3	3	4	3	3	3	3	3	3	3	3	4	3	3	4	4	3	74	67.3
26-Brazil	4	3	4	3	4	5	1	2	4	2	2	3	3	5	3	4	4	3	3	4	3	4	73	66.4
27-Egypt	4	2	4	4	4	3	3	3	3	3	2	4	4	3	4	3	3	3	4	4	3	3	73	66.4
28-Iran	4	3	4	4	3	3	2	2	3	4	3	3	3	3	3	4	3	3	4	3	4	3	71	64.5
29-Qatar	3	4	3	3	4	3	3	3	3	2	3	3	4	3	3	3	3	3	4	3	3	3	69	62.7
30-Samua	4	3	3	4	4	2	3	4	3	3	3	4	4	3	3	2	2	1	4	3	3	3	68	61.8
31-Thailand	4	2	4	4	2	2	4	3	3	3	2	4	3	4	2	3	2	3	4	4	4	2	68	61.8
32-Madagascar	4	3	4	4	4	2	2	2	4	5	4	2	2	1	2	2	4	2	4	4	2	4	67	60.9
33-Mexico	4	3	3	4	2	3	4	3	3	2	3	2	3	3	3	2	3	3	3	2	4	3	65	59.1
34-Morocco	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	3	3	61	55.5
35-Palestine	3	2	3	4	3	2	4	4	4	3	2	4	3	2	1	2	2	2	3	3	1	2	59	53.6
36-Monaco	3	2	1	3	3	1	3	3	4	4	1	2	3	1	1	1	1	1	3	4	1	1	47	42.7
37-Armenia	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	44	40.0

Table 5. Importance and weighting factors of the HFA indicators

Indicator	Importance factor *IF*	Weighting factor W_i	Indicator	Importance factor *IF*	Weighting factor W_i	Indicator	Importance factor *IF*	Weighting factor W_i
I-1	0.54	0.154	I-9	0.65	0.187	I-17	0.1	0.028
I-2	0.79	0.225	I-10	0.017	0.005	I-18	0.1	0.028
I-3	0.05	0.014	I-11	0.05	0.014	I-19	0.1	0.028
I-4	0.13	0.038	I-12	0.02	0.006	I-20	0.1	0.028
I-5	0.10	0.028	I-13	0.1	0.028	I-21	0.1	0.028
I-6	0.08	0.024	I-14	0.1	0.028	I-22	0.1	0.028
I-7	0.05	0.014	I-15	0.1	0.028			
I-8	0.025	0.007	I-16	0.1	0.028			

Table 6. Resilience results obtained from the three methods and the exposure of each country

Country	R_1	R_2	R_3	E (%)	Country	R_1	R_2	R_3	E (%)	Country	R_1	R_2	R_3	E (%)
Fiji	0.84	0.98	0.98	27.7	Germany	0.49	0.82	0.61	11.4	Brazil	0.29	0.73	0.44	9.5
Costa Rica	0.62	0.88	0.78	42.6	Nigeria	0.45	0.79	0.61	12.0	Egypt	0.20	0.66	0.44	4.7
Singapore	0.70	0.89	0.75	7.8	Canada	0.44	0.79	0.60	9.2	Iran	0.24	0.66	0.42	10.1
Japan	0.65	0.90	0.71	45.9	France	0.43	0.78	0.59	9.2	Qatar	0.24	0.64	0.39	30.3
UAE	0.49	0.82	0.73	5.9	Ecuador	0.42	0.78	0.58	16.1	Thailand	0.17	0.63	0.37	13.7
Austria	0.56	0.83	0.70	13.6	Ethiopia	0.35	0.76	0.59	11.1	Madagascar	0.23	0.68	0.39	16.0
United Kingdom	0.48	0.81	0.68	11.6	USA	0.35	0.75	0.57	12.2	Mexico	0.21	0.63	0.35	13.8
Greece	0.48	0.81	0.67	21.1	Chile	0.35	0.77	0.55	12.2	Morocco	0.13	0.54	0.31	13.2
Australia	0.47	0.80	0.65	15.0	Ghana	0.30	0.79	0.53	14.4	Palestine	0.12	0.58	0.30	6.4
Italy	0.41	0.78	0.64	13.8	Argentina	0.25	0.66	0.49	9.5	Monaco	0.08	0.52	0.19	9.25
Cameroon	0.46	0.80	0.63	18.1	South Africa	0.32	0.69	0.48	12.0	Armenia	0.05	0.40	0.16	14.5
New Zealand	0.44	0.79	0.63	15.4	Pakistan	0.30	0.69	0.45	21.1					